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Thermogravimetric Analysis of a Designed Nanoplatelet-Reinforced Composite for Ballistic Shield Using Bamboo Fiber

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Abstract

Incorporating high-strength reinforcements like graphene and Kevlar to enhance composite performance highlights the efficacy of a body armour. this research provides a comprehensive thermal characterization of the developed bamboo ballistic shield composites, validating their impurities performance for protective applications, and make the composite a promising candidate for lightweight ballistic armor, as well as providing compelling evidence for their potential use in ballistic protection applications, through experimental work conducted at two primary locations the Nigerian Institute of Leather and Science Technology (NILEST) and Ahmadu Bello University (ABU), Zaria, Kaduna State. The study's findings not only confirm the effectiveness of using a bamboo, graphene, and Kevlar hybrid but also provide a quantitative framework for future material engineering, allowing for the precise tuning of properties to meet the stringent demands of protective shields. Also, the findings confirmed that the progressive inclusion of graphene nanoplatelets and Kevlar layers did not merely improve these properties, but did so in a predictable and quantifiable manner.

Keywords: *Thermogravimetric, Nanoplatelet-Reinforced, Composite, Ballistic Shield, Bamboo, Graphene, and Kevlar hybrid.*

1. INTRODUCTION

The development of effective soft body armor is vital for ensuring the safety of law enforcement personnel. The overarching goal is to deliver optimal protection while minimizing additional weight and cost. Consequently, there is an urgent need for a systematic approach to refine existing armor systems and innovate new designs (1). The ongoing evolution of body armor reflects the need for enhanced protection against varying levels of threats (2). Research into impact-resistant materials is not only pertinent for traditional defense against combat-related projectiles but also addresses less apparent threats, such as those resulting from high-velocity collisions (3;4;5; 6; 7). The reliance on trial-and-error for designing protective systems is not only cost-prohibitive but also impedes meaningful advancements in design improvement. It is widely recognized that ballistic protection materials should maximize resistance to penetration while minimizing weight. Heavy materials can hinder mobility in wearable armor and increase launch weights for aerospace applications. Thus, there is a critical demand for improved ballistic protection materials capable of withstanding extreme impact scenarios (8). This situation creates an opportunity to explore the use of locally sourced materials in conjunction with graphene to reduce costs effectively. The stabilization of co-continuous microstructure plays a vital role in material applications. Researchers have successfully employed nano fillers to stabilize the co-continuous morphology of composites, as demonstrated in several studies (9; 10; 11). The increasing global security challenges have heightened the demand for effective personal protective equipment, particularly bulletproof vests, which are crucial in absorbing impact and preventing penetration from firearm projectiles and explosion fragments. However, the current market for ballistic protection faces significant accessibility challenges, primarily due to cost barriers. According to (12), the global bulletproof vest market, valued at $1.8 billion in 2022 and projected to reach $3.2 billion by 2032, remains largely inaccessible to many security personnel, especially in economically challenged regions, due to the high costs

associated with traditional materials and advanced manufacturing processes. The primary challenge lies in the economic constraints that limit the widespread adoption of protective gear among local security personnel, particularly in the context of global economic inflation.

The utilization of composite materials has proven to be transformative in various applications due to their significant advantages, including weight reduction, enhanced corrosion resistance, improved fatigue endurance, and design flexibility. As the advancements in weaponry continue to escalate, there is an urgent need to enhance personal protective equipment, particularly ballistic shields, to safeguard individuals from ballistic threats. Ongoing modifications to graphene-based composites are crucial for improving flexibility and hardness in ballistic applications. The unique ability of graphene nanoplatelets to disperse uniformly in various chemical matrices facilitates their incorporation into a wide range of materials, including plastics, polymers, nylons, rubber, and ceramics. This incorporation significantly enhances the mechanical strength, hardness, and robustness of these materials, while also improving their thermal and electrical properties and increasing surface roughness and barrier capabilities. The integration of locally sourced materials, such as bamboo, with graphene nanoplatelets presents an innovative approach to the development of advanced ballistic shields. Bamboo is not only abundant and easily cultivated but also represents a sustainable resource that can contribute to local economies. By promoting the cultivation of bamboo, this research has the potential to create job opportunities for rural communities, thus fostering economic development while simultaneously enhancing the technological capabilities of ballistic protective equipment. In recent years, there has been a growing interest among researchers and engineers in leveraging bamboo for the production of ballistic shields (13). As a renewable and sustainable material, bamboo possesses promising characteristics that could significantly enhance the manufacturing of ballistic shields, offering improved protection for military personnel, law enforcement, and security teams. The composition of ballistic shields is pivotal in determining their effectiveness and reliability in protecting against ballistic threats (14). The materials utilized in the construction of these shields must possess specific characteristics, including high tensile strength, impact resistance, and durability (15). Furthermore, it is essential for the composition of ballistic shields to achieve an optimal balance between providing adequate protection and maintaining a lightweight structure, which enhances user maneuverability. To address existing limitations and improve overall performance, advancements in the composition of ballistic shields are necessary (14). Potential enhancements to the composition may include;

i. Incorporating Bamboo Composites: These materials exhibit superior ballistic performance and reduced weight compared to traditional aramid fabrics (15).
ii. Exploring Graphene-Based Nanomaterials: The excellent tensile strength and specific penetration energy of graphene could serve as a replacement for conventional materials like Kevlar-29 (14).
iii. Utilizing Layered Graphene Sheets: Atom-thick graphene sheets have demonstrated greater strength than steel in impact absorption, which can significantly enhance the resilience and strength of ballistic shields.

Ballistic shields are vital tools for law enforcement and military personnel, providing protection against bullets and other ballistic threats (16). However, several factors necessitate improvements in ballistic shield design. Firstly, the increasing prevalence of high-powered firearms presents a significant challenge to traditional ballistic shield designs. Modern firearms, including assault rifles and high-caliber handguns, can easily penetrate standard ballistic shields, rendering them ineffective in particular scenarios. Secondly, the current weight and size of ballistic shields can impede mobility and agility, limiting the effectiveness and responsiveness of law enforcement officers in dynamic, fast-paced situations. Thirdly, the visibility provided by existing ballistic shield designs is often insufficient, hindering users' ability to accurately assess their surroundings and engage with potential threats (17). In situations where ballistic shields are utilized for offensive, defensive, or patrol purposes, a perimeter is established during call-out applications, with the hope that the subject will surrender peacefully. However, these situations can extend for hours as negotiations occur. Should the situation escalate into violence, officers must seek cover, utilizing whatever is available, including walls, trees, vehicles, and ballistic shields (18). Thus, this study focuses on the development and characterization of graphene nanoplatelet-reinforced bamboo fiber composites specifically designed for ballistic shield applications, and specifically studying the thermal properties of the developed composites, utilizing advanced characterization techniques. With the aim, to contribute to the field of materials science by providing insights into innovative composite materials for enhanced ballistic protection.

2. MATERIALS AND METHODS

2.1 MATERIALS AND EQUIPMENT

The materials and experimental methodology employed in this study consist of two matrix systems: Epoxy resin (Epochem 105) with hexamethylene tetramine hardener, and a vinyl ester

resin system. The reinforcement materials include indigenous bamboo fibers, kenaf fibers, high-purity graphite powder (99.99%), and commercial grade aramid fabric (Kevlar). Various processing chemicals were also employed, such as N-methyl-2-pyrrolidone (NMP) and N-cyclohexyl-2-pyrrolidone (NCP) of analytical grade, reagent-grade sodium hydroxide, and silane coupling agents. The experimental work was conducted at two primary locations: the Nigerian Institute of Leather and Science Technology (NILEST) and Ahmadu Bello University (ABU), Zaria, Kaduna State. The research methodology encompasses material synthesis, composite fabrication, and comprehensive characterization protocols.

2.1.1 Equipment and Instrumentation

The experimental work required an extensive array of processing equipment, such as tabulated below;

Table 1: *Laboratory Equipment used for TGA, XRD, and SEM Experiments*

S/N	EQUIPMENT	MANUFACTURER/MODEL NO.	SOURCES
1	Thermogravimetric Analysis (TGA)	Q5000 IR (TA Instruments) thermo-analyzer	FUTMINNA, Minna, Niger
2	Scanning Electron Microscopy (SEM)	Thermo Fisher Scientific (Model no: Prisma E)	NSRMEA, Kaduna
3	X-ray Diffractometory Analysis (XRD)	PANalytical X'Pert PRO	ABU, Zaria

2.1.2 Design and Fabrication of Ballistic Shield Nanoplatelet-Reinforced Composite Samples

This section describes the successful design of the ballistic shield nanoplatelet-reinforced composites using bamboo fiber. The final product of the ballistic shield samples is shown in Figure 1. The specimens produced were labeled to reflect their reinforcement level and layering sequence:

i. Non-woven Reinforced Bamboo (nBB)
ii. Woven Reinforced Bamboo (wBB)
iii. Woven Reinforced Bamboo-Kevlar (wBK)
iv. Woven Reinforced Bamboo-Kevlar-Bamboo (wBKB)
v. Woven Reinforced Bamboo-Kevlar-Bamboo-Kevlar (wBKBK)

(a) (b) (c)

Figure 1: *(a) One layer of woven-Bamboo and Kevlar. (b) Two layers of Bamboo with Kevlar in-between. (c) Two layers of Bamboo and Kevlar in-between each other*

2.1.3 Thermal Characterization

Thermal properties were examined using Thermal Gravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC). Where TGA was employed to determine the composite's thermal stability and degradation temperatures by continuously measuring the weight change as a function of temperature.

Figure 2: *Thermogravimetric Analysis machine for thermal stability test*

The DSC provided insights into melting points, glass transition temperatures, and crystallization behavior, offering information about the thermal transitions that occur within the composite.

2.1.4 X-ray diffraction (XRD)

X-ray diffraction (XRD) was used to identify the crystalline phases present and quantify the crystallinity index within the composite, while Fourier transform infrared spectroscopy (FTIR) was used to detect functional groups and chemical bonding interactions. As the Raman spectroscopy offered additional insight into the structural integrity and electronic properties of the graphene nanostructures incorporated into the composite. Through the application of these characterization techniques, a

comprehensive understanding of the material's performance was obtained. This understanding was crucial in optimizing the composite's design for the intended application. The integration of these techniques allows for the identification of key factors influencing the composite's effectiveness, ultimately contributing to the development of improved materials for ballistic protection.

Figure 3: *Scanning Electron Microscopy for surface morphology test*

3.0 RESULTS AND DISCUSSION

3.1 SCANNING ELECTRON MICROSCOPY

Scanning electron microscopy (SEM) was done in accordance with ASTM E-986 standard. A piece of cross section of the sample weighing 0.5 g was cut and mounted on the sample holder. The sample holder was carefully inserted beneath the magnification screen of the machine and the chamber was closed. The microscopic features of the sample were viewed and a particular area of the microscopic feature was magnified under electron microscopy at different magnifications until a clear electron feature of the sample was viewed and recorded accordingly. The density and average particle size of the specimens was viewed at 1500 × 179 µm for a range of 50µm. the SEM images of the wBB and wBK are shown in Figure 4 and 6, Graphical presentation the impurities in Figure 5 and 7, while Table 1 and 2 shows the SEM result of the impurities found in the matrix (wBB and wBK), as well as their Atomic Concentration and weight Concentration.

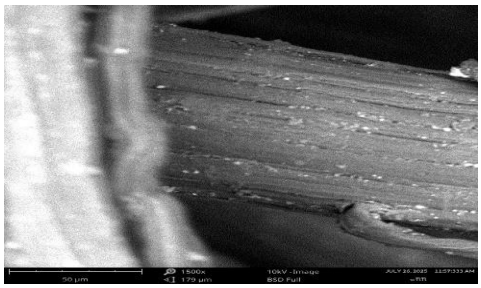

Figure 4: *SEM images of the wBB.*

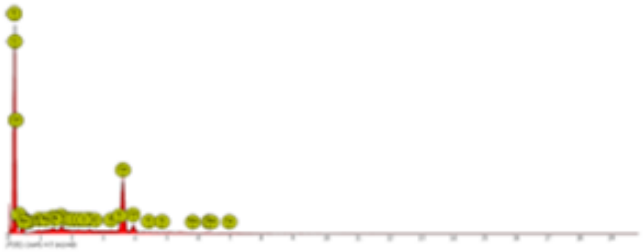

Figure 5: *Graphical presentation the impurities in wBB*

Table 1: *impurities in wBB matrix.*

Element No.	Element symbol	Element name	Atomic Conc.	Weight Conc.
6	C	Carbon	57.32	53.69
8	O	Oxygen	31.98	44.66
1	H	Hydrogen	5.80	5.80
7	N	Nitrogen	4.00	3.92
14	Si	Silicon	0.27	0.53
13	Al	Aluminum	0.20	0.37
26	Fe	Iron	0.08	0.29
11	Na	Sodium	0.18	0.29
22	Ti	Titanium	0.04	0.12
17	Cl	Chlorine	0.05	0.12
12	Mg	Magnesium	0.07	0.12
19	K	Potassium	0.03	0.07
25	Mn	Manganese	0.00	0.00
15	P	Phosphorus	0.00	0.00
16	S	Sulfur	0.00	0.00

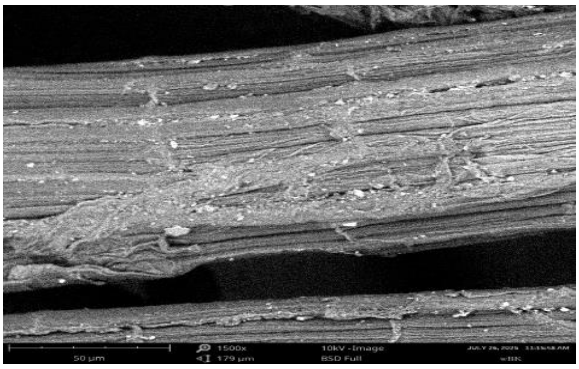

Figure 6: *SEM images of the wBK*

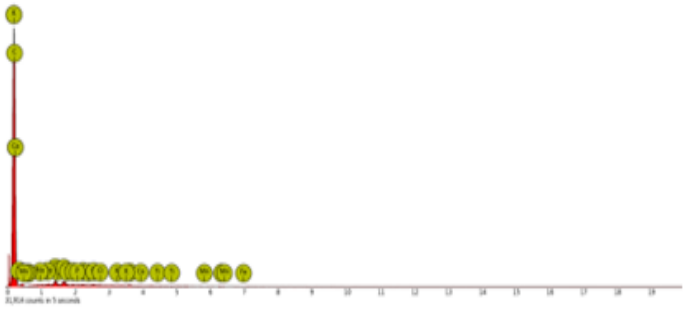

Figure 7: *Graphical presentation the impurities in wBK*

Table 2: *impurities in wBk matrix*

Element No.	Element symbol	Element name	Atomic Conc.	Weight Conc.
6	C	Carbon	76.55	74.64
8	O	Oxygen	10.36	10.79
7	N	Nitrogen	7.37	7.71
1	H	Hydrogen	5.00	5.00
14	Si	Silicon	0.30	0.69
26	Fe	Iron	0.07	0.31
12	Mg	Magnesium	0.09	0.18
20	Ca	Calcium	0.05	0.18
11	Na	Sodium	0.08	0.14
17	Cl	Chlorine	0.05	0.14
16	S	Sulfur	0.05	0.12
15	P	Phosphorus	0.04	0.10
19	K	Potassium	0.00	0.00
22	Ti	Titanium	0.00	0.00
25	Mn	Manganese	0.00	0.00

3.2 THERMOGRAVIMETRIC ANALYSIS

Thermogravimetric analysis (TGA) was performed using a Q5000 IR (TA Instruments) thermo-analyzer instrument under nitrogen and air conditions. Samples were measured in an alumina crucible with a mass of about 12-14 mg. Composites in an open pan was tested at temperature ranging from 25 to 800^{o}C with a heating rate of 10^{o}C/min. Figure 8 shows the TGA graph for wBB using the weight against temperature, while Figure 9 shows the TGA graph for wBB using the weight and Derivative weight against temperature. Also Figure 10 and Figure 11, shows the TGA graph of wBK, as the weight of the Matrix is plotted against temperature, as well as weight and Derivative weight against temperature.

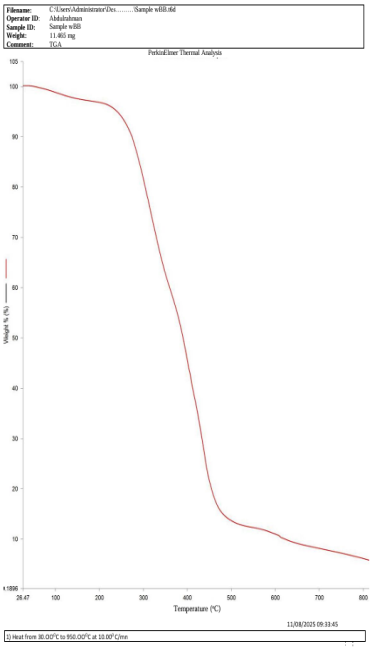

Figure 8: TGA for wBB using the weight against temperature

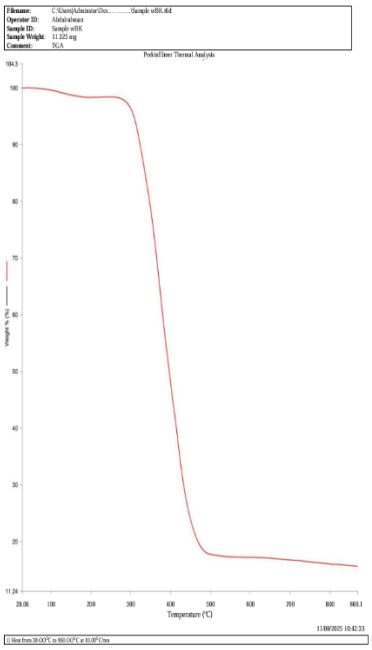

Figure 9: TGA for wBK using the weight against temperature

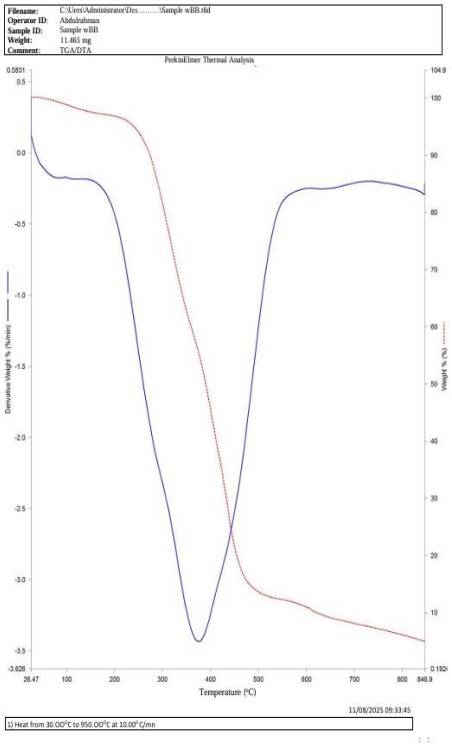

Figure 10: *TGA for wBB using the weight and Derivative weight against temperature*

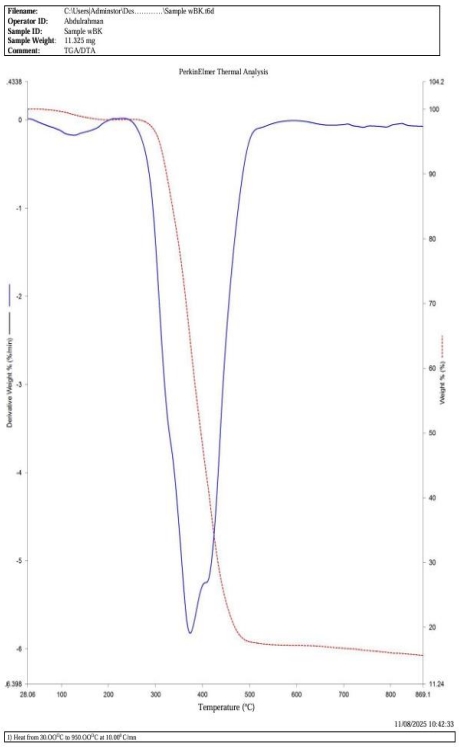

Figure 11: *TGA for wBK using the weight and Derivative weight against temperature*

3.3 X-RAY DIFFRACTOMETRY ANALYSIS

X-ray diffraction (XRD) analysis of the composite samples was carried out using an X-ray diffractometer PANalytical X'Pert PRO equipped with Cu Kα radiation source (λ = 1.5406 Å). The instrument was operated at 40 kV and 40 mA, with data collected over a 2θ range of 5°–80° at a step size of 0.02° and scan rate of 2°/min. Phase identification was performed by comparing the obtained diffraction patterns with standard reference data from the ICDD PDF-2 database. Figure 12 and Figure 13, shows the graphical variation of the XRD for the 2 layers of woven-Bamboos and 2-layer of woven-Bamboo and Kevlar.

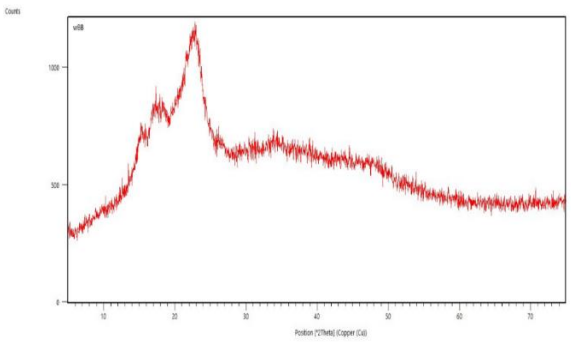

Figure 12: XRD Graph for 2 layers of woven-Bamboos

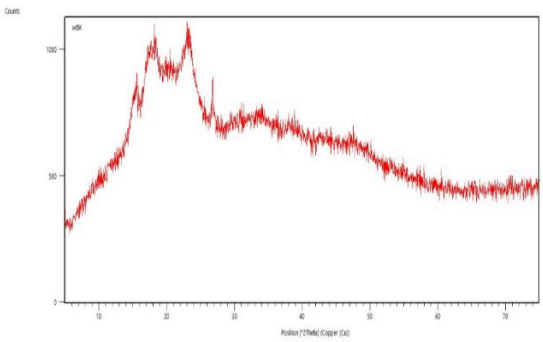

Figure 13: XRD Graph for 2-layer of woven-Bamboo and Kevlar

The XRD data is used to identify the crystalline phases and measure the degree of crystallinity, which directly influences the mechanical and thermal properties. The data from SEM-EDX, TGA, and XRD, therefore provides a comprehensive understanding of the materials' microstructural and thermal behavior, establishing the fundamental properties of the developed composites.

4.0 CONCLUSION

This study successfully investigated the development and thermal characterization of a graphene nanoplatelet-reinforced bamboo fiber composites, providing compelling evidence for their potential use in ballistic protection applications. The research confirmed that the progressive inclusion of graphene nanoplatelets and Kevlar layers did not merely improve these properties, but did so in a predictable and quantifiable manner. These results are well-aligned with the broader scientific literature, which highlights the efficacy of incorporating high-strength reinforcements like graphene and Kevlar to enhance composite performance. However, the study also provided nuanced insights into the complex trade-offs of composite design. This is consistent with the well-known principle that adding rigid reinforcing agents can sometimes make a composite more brittle. The findings thus underscore the importance of balancing competing mechanical properties when designing materials for specific applications. In conclusion, this research provides a comprehensive thermal characterization of the developed composites, validating their mechanical performance for protective applications, and make the composite a promising candidate for lightweight ballistic armor. The study's findings not only confirm the effectiveness of using a bamboo, graphene, and Kevlar hybrid but also provide a quantitative framework for future material engineering, allowing for the precise tuning of properties to meet the stringent demands of protective shields.

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